FINAL REPORT

AN ELECTROLYTIC DAMPING RESISTOR FOR
THE MICROPARTICLE ACCELERATOR

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AN ELECTROLYTIC DAMPING RESISTOR FOR THE
MICROPARTICLE ACCELERATOR

A damping resistor of the electrolytic type employing copper sulphate solution has been designed and tested in the microparticle accelerator generator-switch assembly. An assembly drawing of the resistor is included as Figure 1. The design was conceived in accordance with the data provided in a note by Bishop and Edwards which is reproduced as Appendix I. The volume of electrolyte is 2.82 cc and the length to-area ratio is 28.0 cm^{-1} so that the resistance is given by:

$$R = 28.0 \, \rho \tag{1}$$

where ρ is the resistivity of the electrolyte in ohm cm.

A resistance value of 1500 ohms, more or less, was desired since this yields a time constant of about 150 nsec with the ~ 100 pF stage capacitance. Seven time constants (corresponding to decay to the 0.1% level) than transpire in a little over 1 μsec. The required electrolyte resistivity is then 53 ohm-cm and corresponds to a concentration of ~ 100 gf solute per liter of water.

For the test, the value of the prototype resistor was 1400 ohms as measured by a Simpson meter at low voltage. As noted in Appendix I, the high voltage resistance value may have been 10%, or somewhat more, lower. This value not particularly critical, so precise knowledge of it is unnecessary. The testing consisted of about 5000 discharges at 600 kv over a period of 4 days followed by another 5000 discharges at 400 to 500 kv, again over a period of 4 days. Generator voltage was monitored by means of the column current which was corrected for the non-linearity of the column resistance by means of the new ultra-linear generating voltmeter circuit. The calibration showed the column resistance to be down by about 7% at 500 kv, implying a column resistor voltage coefficient of 1.1 ppm/v, a value falling within the resistor manufacturer's stated range for this parameter. During testing, the time between discharges was varied from a few seconds to over 60 seconds.

1

CU SO₄ SOLUTION

LUCITE BODY

$\frac{13}{16}$ DIA.

4 $\frac{1}{4}$"

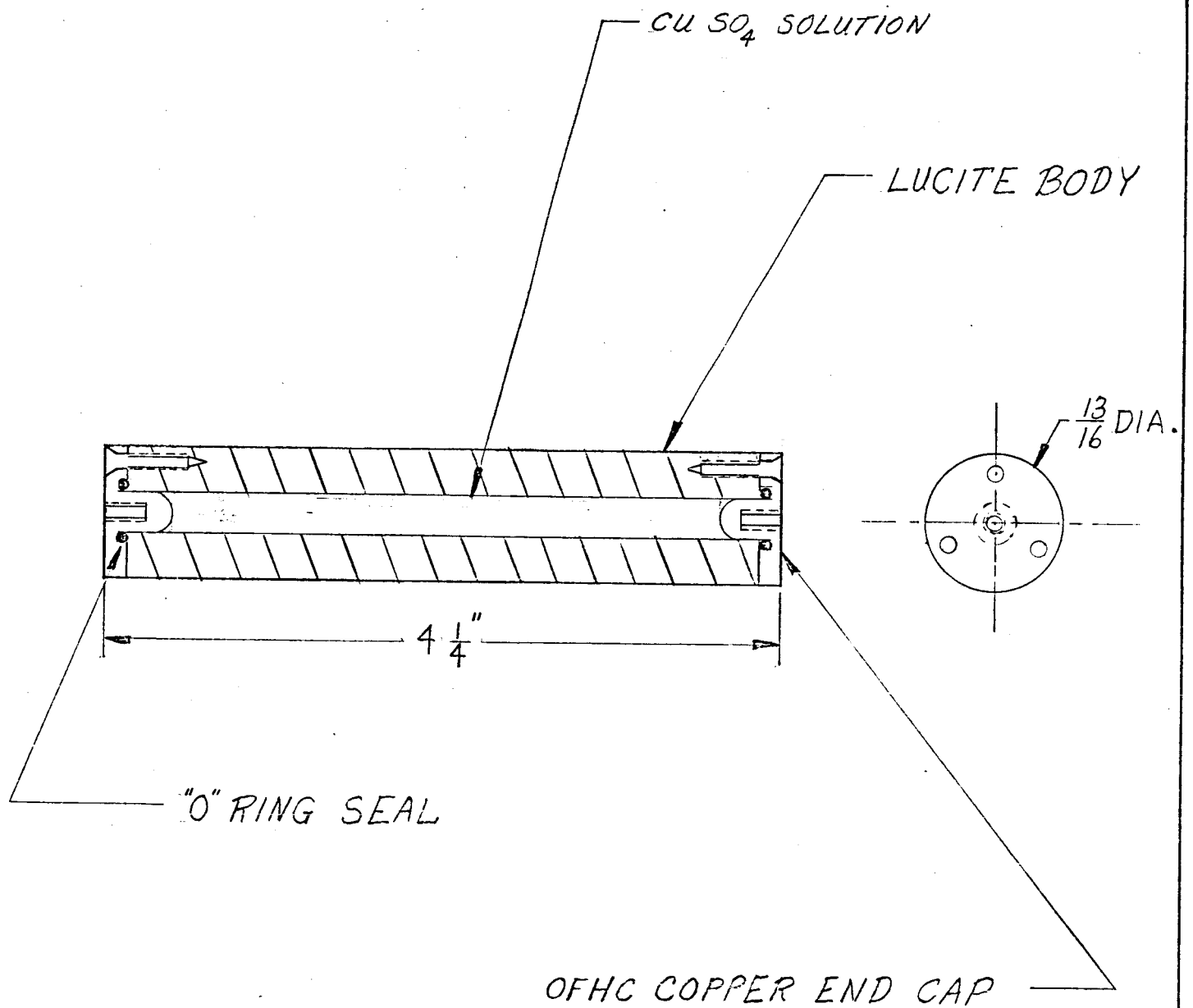"O" RING SEAL

OFHC COPPER END CAP

Figure 1.   Cross-Section of Electrolytic Resistor (Full Scale)

The tests demonstrated convincingly the suitability of the electrolytic resistor in this application. No evidence whatsoever of flashover or any other form of electrical damage could be found after about 10,000 total discharges, many at voltages well above projected operating levels. It should be noted that the capacitance being discharged was only about half what it will be in actual use because of the absence of bushing and drift tube. The discharge energy and duration were thus about half of the expected operational values. The resistance value proved to be quite stable, the measurements showing a slight increase to just under 1500 ohms by the end of the tests. The magnitude of the increase is not reliable since it is within the measurement uncertainty of the Simpson meter but the trend is probably significant.

The slight increase in resistance was accompanied by the appearance of a few small bubbles in the electrolyte. These appeared to grow slowly as the tests proceeded but did not seem to affect the operation of the resistor. Before the discharges were begun, the resistor was allowed to remain inactive in the pressurized environment for 4 or 5 days and no bubbles were observed to form, so one is inclined to conclude that the application of voltage caused the bubbles. On the other hand, others have observed the formation of such bubbles after extended periods of storage of electrolytic resistors at one atmosphere and room temperature, and have concluded they arise from the desorption of gases from surfaces and the eventual wetting and filling of small crevices and fissures. During extended storage, the bubbles do not grow indefinitely large, but rather seem to approach an equilibrium size, as might be expected. It could be that the application of voltage hastens the desorption processes and causes the bubbles to appear more rapidly than during inactivity, but it is also possible that the growth of bubbles is at least partly due to the decomposition of water by electrolysis during the discharge. In the latter case, the bubbles would not approach an equilibrium size but would grow indefinitely until resistor operation was seriously impaired. The tests which have been performed are not adequate to determine which hypothesis is correct, but do indicate that a very large number of discharges (> 10,000 at half energy, or perhaps > 5,000 at full energy) can be withstood without significant impairment of function.

The duty cycle of the microparticle accelerator is such that at least one year's operation can be anticipated before servicing (by topping with distilled water) may be necessary.

APPENDIX I

ELECTROLYTIC RESISTORS IN PLASMA
PHYSICS RESEARCH

LABORATORY NOTE

Electrolytic resistors in Plasma Physics research

1. INTRODUCTION

At the beginning of 1959 a requirement arose for a resistor of 0·14 Ω at 200 kV with an inductance of 30 nH, capable of passing pulse currents of 40 kA and of absorbing an energy of 1 MJ at 700 kA peak in the event of a circuit fault.

Various designs of metal and carbon resistors were considered but after preliminary tests with copper electrodes in a copper sulphate solution it was decided that this type of resistor had most promise and was adopted in the final design. It has given satisfactory service now for more than four years. Details of this resistor are shown in Table 1 under the heading 'Capacitor protection and pulse shaping'.

Since 1959 many other resistors have been designed and used for a variety of similar duties such as charging resistors (5000 Ω, 100 kV), stress grading of cable terminations (7500 Ω, 100 kV), and cable impedance matching resistors (8 Ω, 100 kV). The physical details of some of these resistors are tabulated in Table 1, and the construction of three types shown in Fig. 1.
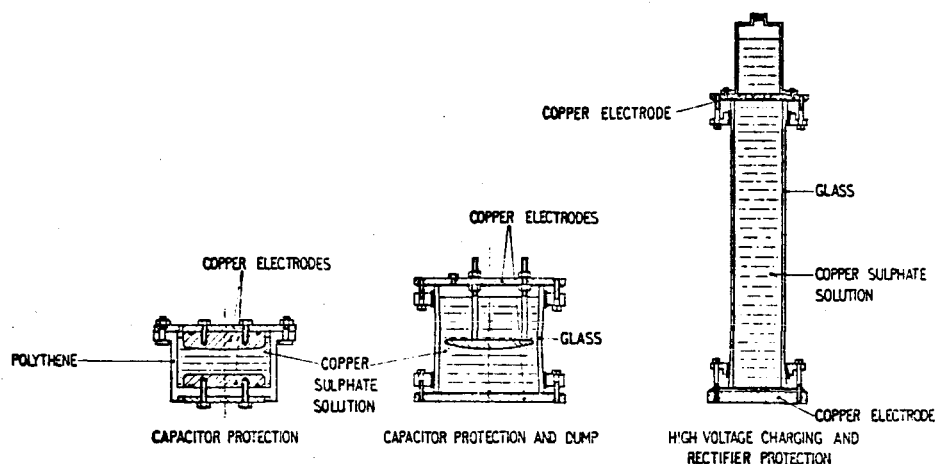
FIG. 1.—Three types of electrolytic resistor.

The basic data on these resistors has been gained partly from their use in service and partly from brief laboratory tests aimed at establishing the limitations of the designs.

2. BASIC DATA

2.1 *Electrical resistance*

The curves in Fig. 2 show the resistivity of solutions (Ω-cm) plotted against the concentrations (g/l) for solutions of copper sulphate and potassium dichromate in demineralized water at 20°C. It will be noticed that the saturated solutions have minimum resistivities of about 20 Ω-cm and maximum resistivities of more than 10^5 Ω-cm. It is possible to use any value within this range. It has been found better, however, not to work at values of resistivity greater than say 10^4, as accuracy of the resistor value will depend too critically on concentration, or less than 30 Ω-cm because the solute

Laboratory note

TABLE 1.—TYPICAL RESISTOR CHARACTERISTICS

Resistor type	Number in circuit	Active length (cm)	Active area (cm²)	Volume (l)	Resistance (Ω)	Resistivity (Ω-cm)	Concentration (g/l)	Operating voltage (kV)	Electrical stress (kV/cm)	Current flow Forward → Reverse →	Current density (mA/cm) Forward → Reverse →	Energy absorption (kJ)	Frequency or time constant	Coulombs/pulse Forward → Reverse →	Duty cycles
High voltage charging and rectifier protection	1	122	83	10	500	3400	0·53*	100	8·2	100 mA → / ↓ ¼ A	1·2 → / ↓ 6	1250	D.C. → / 10⁻⁸ sec ←	2	30 sec every 3 min / Fault
Capacitor protection and dump	4	23	350	8	1000	15,200	0·095*	100	4·3	2·5 mA → / ↓ 100 A	0·07 → / ↓ 290	1000	D.C. → / 25 sec ←	10 → / ↓ 40	30 sec every 3 min / Dump
Capacitor protection and dump	5	16	350	5½	6	175	19*	14	0·87	2 A → / ↓ 2300 A	5·7 → / ↓ 6600	700	D.C. → / 3 × 10⁻⁵ sec ←	7 → / ↓ 7	30 sec every 3 min / Dump
Make switch termination	40	10	25	½	5000	1500	1†	100	10	20 A	800	31	130-250 kc/s	2 × 10⁻⁴	1 pulse every 3 min
Load assembly cable termination	50	10	100	½	5000	10,000	0·1†	100	10	20 A	800	31	5-16 kc/s	2 × 10⁻⁴	1 pulse every 3 min
Test model June 1959	1	2·5			0·25		*	20	8	70,000			1 × 10⁻⁵ sec		Occasional
Test model July 1959	1	7·5	1·82	1·4	1	33	140*	4V RMS		5·6 A Peak	31	170	50 c/s	3·6 × 10⁻² per ½ cycle	Continuous
Test model May 1963	1	122	83	10	500	3400	0·53*	48V		100 mA	1·2	1250	D.C.		Continuous
Capacitor protection and pulse shaping	16	12·5	1100	1·38	0·14	12·55	300‡	100	8	12 mA → / 40 kA ← / 700 kA →	10⁻³ → / 36000 → / 640000 →	1650	D.C. 10 kc/s 40 kc/s	↑↓↑ ¼ 4	30 sec every 3 min / 1 pulse every 3 min fault

* Copper sulphate CuSO₄·5H₂O.　　† Potassium dichromate K₂Cr₂O₇.　　‡ Copper sulphate CuSO₄·5H₂O and sulphuric acid H₂SO₄.

tends to come out of solution at the higher concentrations. If a value of resistivity below 30 Ω-cm is required it is more satisfactory to mix a solution of about 40 g/l and add acid, as is shown in Fig. 2 to get down to the resistivity required.

We have only used solutions of potassium dichromate at concentrations of 0·1 and 1·0 g/l.

The limited tests which have been done to established resistivity changes with temperature of solution indicate that for a rise in temperature of 30°C above ambient a fall of about 30 per cent in resistivity may be expected. However above 50°C the fall in resistivity with increase in temperature is less pronounced. Some control of temperature is therefore necessary if resistor accuracy is important.

The resistivity of a solution falls by about 10 per cent for an applied stress of 18 kV/cm. (MOSCH, 1955). In our designs we do not exceed 15 kV/cm.

On the other hand, with very low stresses (about 10 V/cm) the resistance increases, presumably due to films on the electrode surfaces.
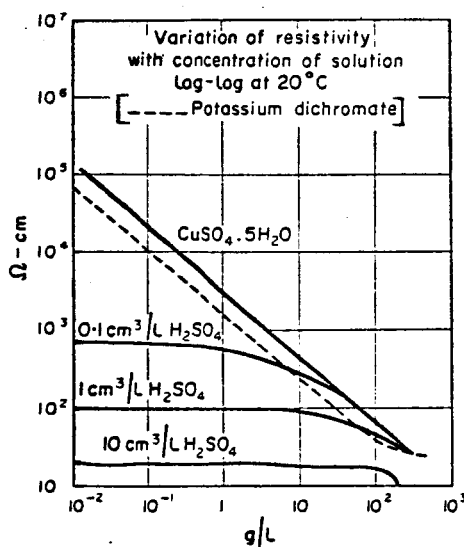

FIG. 2.

Our tests have been made with direct current and alternating current up to 1000 c/s. In service resistors have been used in circuits with frequencies as high as 250 kc/s. No dependence of resistance on frequency has been found. However 50 c/s alternating current is normally used to measure resistor values to avoid any polarization effects. Skin depth does not become a problem unless the diameter of the resistor approaches 50 cm and the frequency exceeds 1 Mc/s.

2.2 Energy and current ratings

The very earliest tests showed that all the energy dissipated in an electrolytic resistor went into heating the liquid. This was true even for pulses of current lasting 1 msec.

For pulse duty it is therefore only necessary to arrange for a sufficient volume of electrolyte to keep the temperature rise to a reasonable figure. For a 30°C temperature rise (our normal design figure) about 120 J/cm³ can be absorbed. This gives rise to an expansion of 0·6 per cent. If resistance value is not important, the electrolyte can be raised just short of boiling point. For continuous ratings for which natural cooling is not good enough, cooling by internal coils of Polythene tubing carrying mains water have been used successfully.

When a resistor carries a high current of I A a force of $3I^2/400$ dynes pushes the electrodes apart. One third of this is due to the magnetic pressure directly on the electrodes and two thirds is due to the hydrostatic pressure caused by the magnetic pressure operating on the liquid ('pinch effect'—NORTH-RUP, 1907).

In these designs it is clear that the charge flow and current density are greatly in excess of normal electroplating practice. Instead of the fractions of an A/cm² used in electroplating we have been passing several hundreds of amps per square centimetre. The reason that such departures from

electroplating practice are nevertheless satisfactory is that the criteria for satisfactory operation are different.

In electroplating it is necessary that the metal deposited should form a smooth adherent film on the parent metal and there should be no degeneracy of the solution. However for a successful resistor it is necessary only that its overall value should be retained and that electrical flashover in the solution must not occur.

Perfect plating does not often occur in our resistors but this does not worry us as the resistor criteria are not violated. However, to minimize the effects of bad plating it is our normal practice to use smooth rounded electrodes, to place the electrodes vertically one above the other allowing room for the electrolyte to circulate and to place the cathode at the bottom in such a way that any growths which form fall below the lower electrode and do not climb the walls.

2.3 *Electrodes*

With copper sulphate solutions it has been found absolutely imperative to use only copper electrodes. Any other material in contact with the electrolyte—even brazing or solder—has been found to erode and contaminate the solution.

This stringent requirement has not been found necessary with sodium and potassium dichromate solutions, at least at the concentrations used by us (0·1 and 1·0 g/l). With these solutions stainless steel, brass and copper electrodes have all behaved satisfactorily at least at the lower current densities (see Table 1).

2.4 *Effect of air bubbles in the solution*

If an air space exists in the electrolyte between the electrodes the voltage stress at that point may be sufficient to break it down and cause a discharge to take place. If the air space takes the form of a thin film across the surface of one electrode, perhaps because the level of the liquid has fallen in a resistor having one electrode above the other, then all the energy in the circuit may be deposited in the air space causing heating and local boiling of the liquid. If the energy is deposited rapidly enough pressures will be produced which may be explosive and shatter the assembly.

3. CONCLUSIONS

The electrolytic resistor offers the principal advantage of high-energy absorption with flexibility in the choice of resistor value over a very wide range. Furthermore with a series of standard electrodes and tubes this range can be extended still further.

The principal disadvantage is that there is a liquid to be contained and occasionally topped up.

On direct current, for one filling of electrolyte, the resistors have a limited though long life depending on duty. Eventually the solution gets deprived of copper ions. On pulsed or alternating currents we have not found any limits.

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